Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6770--08-9147

Ar-Xe Laser: The Path to a Robust, All-Electric Shipboard Directed Energy Weapon

J.P. Apruzese

Pulsed Power Physics Branch
Plasma Physics Division

J.D. Sethian

Laser Plasma Branch
Plasma Physics Division

J.L. Giuliani

Radiation Hydrodynamics Branch
Plasma Physics Division

M.F. Wolford

Laser Plasma Branch
Plasma Physics Division

December 18, 2008

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
18-12-2008

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Ar-Xe Laser: The Path to a Robust, All-Electric Shipboard Directed Energy Weapon

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
J.P. Apruzese, J.D. Sethian, J.L. Giuliani, and M.F. Wolford

5d. PROJECT NUMBER
67-8545-08

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory, Code 6770, 6730,
and 6720
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/6770--08-9147

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph St.
Arlington, VA 22203-1995

10. SPONSOR / MONITOR'S ACRONYM(S)

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
High Energy Lasers (HELs) long ago demonstrated their potential to destroy missiles in flight, a capability which could significantly reduce the threat to the fleet arising from anti-ship cruise missiles. However, no HELs have been deployed to date. Until recently, there was no laser that had credible prospects of meeting the Navy's requirements for safety, power, size, beam quality, electrical drive, and atmospheric propagation. The electron beam pumped Ar-Xe laser has been investigated in an ONR-sponsored 6.1 program at NRL. The results of this program are summarized in this Memorandum Report, and indicate that the Ar-Xe laser has strong potential to meet these requirements. A technical road map which scales the present parameters of the Ar-Xe laser to a deployable system is presented.

15. SUBJECT TERMS

Directed energy weapon	Electron beam pumping	Pulsed power
High energy laser	Ar-Xe laser	Anti-ship missile defense

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John P. Apruzese
Unclassified	Unclassified	Unclassified	UL	18	**19b. TELEPHONE NUMBER** *(include area code)* (202) 767-2939

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTENTS

I. Introduction

In 1978, the U. S. Navy accomplished one of the most important milestones in the search for a Directed Energy Weapon (DEW) with the first shootdown of a missile in flight by the Navy-ARPA Chemical Laser (NACL). Despite three decades of subsequent effort, there is still no operational shipboard directed energy laser weapon. This is primarily due to the fact that, until recently, no suitable laser candidate existed. "Suitable" means good maritime atmospheric propagation, durability to withstand the rigors of a shipboard environment, adequate power, electrical drive, efficiency, beam quality, and safe operation. NRL's Plasma Physics Division has conducted a 5-year 6.1 program (Oct. 2003 – Sept. 2008), which investigated the electron beam pumped Ar-Xe laser. This program met all of its scientific and technical objectives, and we believe that the Ar-Xe laser can meet the Navy's requirements: (1) The wavelength is 1.733 microns, which has an absorption of only 2.2% per km in a maritime atmosphere. (2) The laser uses rugged pulsed power technology, which is ideally suited for the all-electric warship of the transformed Navy. (3) The laser medium is an inert gas that is recycled through a closed loop without combustion or exhaust. (4) The laser operates at an "eyesafe" wavelength which greatly reduces operational safety risks associated with reflection and scattering of the primary beam.

This integrated theoretical / experimental program used the NRL Electra laser [1]. Electra is being developed as a Krypton Fluoride (KrF) laser for fusion energy and is sponsored by the Department of Energy's (DOE) High Average Power Laser (HAPL) program. DOE investment well exceeds $50 M to date, a factor of at least 30 times greater than the $1.8 M total 5-year cost of the 6.1 program itself. Our 6.1 Ar-Xe

---

Manuscript approved October 20, 2008.

research using Electra has enabled us to identify a credible path to a DEW class laser. In the following sections, we describe the basic features of the Ar-Xe laser, summarize the achievements of the 6.1 program, and delineate the technical roadmap for carrying this research to fruition as a practical shipboard DEW.

II. Basic properties of the Ar-Xe laser

When a high energy (~ hundreds of keV) electron beam is launched into a mixture of the inert gases argon and xenon, the gas becomes partly ionized. The ionized species interact through complex atomic and molecular ionic processes and lead to the preferential population of an upper excited state in neutral xenon (see Fig. 1). This results in a population inversion and lasing at 1.733 microns. Even in a maritime tropical atmosphere, with 70% relative humidity at 80º F, the absorption at this wavelength is only 2.2% per km [2]. Within a microsecond or so after passage of the pulsed electron beam, full relaxation of the gas has occurred, and it returns to its quiescent, neutral, chemically inert state. Thus, not only does this laser propagate well at sea, it recycles its lasing medium, and there is no hazard to the crew arising from the materials needed to make it work. Furthermore, the electron beams which pump the laser medium are readily producible by rugged, industrial pulsed power generators well suited to the all-electric warship of the future. The electron beam quality and kinetic energy requirements are substantially less stressing than those needed for a free electron laser (FEL) and the radiation shielding requirements are also significantly reduced. Clearly, this laser has the potential to be an attractive DEW option for the Navy.

In order to produce a uniform gas laser medium of large volume, two counter-propagating electron beams have been employed in gas lasers such as the Electra KrF laser at NRL. This strategy is also applicable to the Ar-Xe laser. The critical components

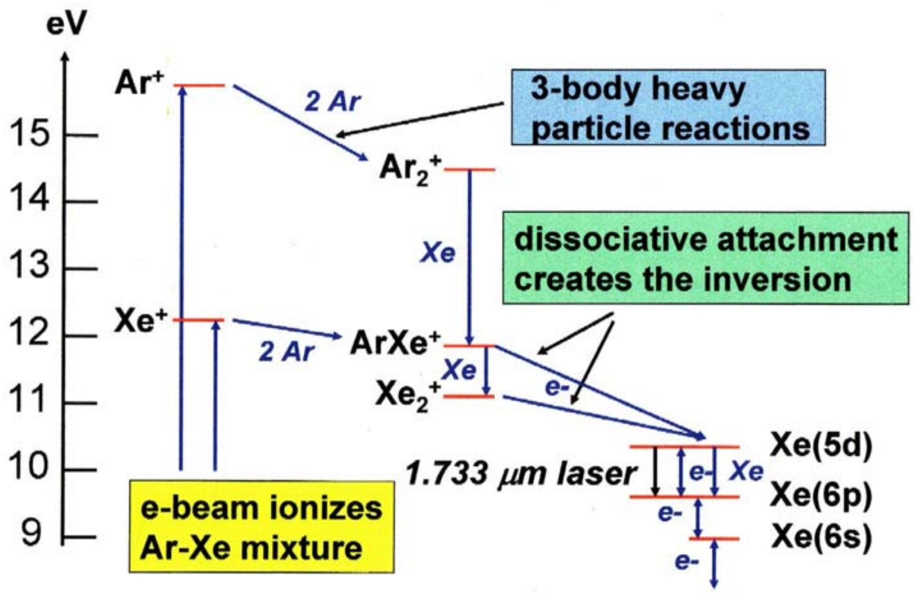

FIG. 1. Reaction kinetics, as presently understood, which produce population inversion in the Ar-Xe laser.

in the vicinity of the laser cell are illustrated in Fig. 2. This figure portrays the implementation of the Ar-Xe laser at NRL on the Electra facility. Each electron beam draws its energy from a separate capacitor bank which is discharged through a pulse-forming line into a vacuum diode. Peak voltage pulses of ~ 500 kV at each diode launch electron beams from a cathode surface into the gas from opposite sides of the rectangular laser cell. To isolate each vacuum diode from the laser gas, a grill-shaped structure, known as a hibachi, supports a pressure foil and a separate anode foil. Typically, these foils are composed of stainless steel or titanium. The laser gas flows between the two foils within a recirculator which serves to cool and quiet the laser gas. Fig. 3 is a photograph of the Electra facility showing the identical capacitor banks that power the diodes. The pulse forming lines are visible (blue tubes) in the photo as are the racetrack-

shaped magnets (black) which guide the electron beams. The rectangular laser cell is in the central core between the magnets.

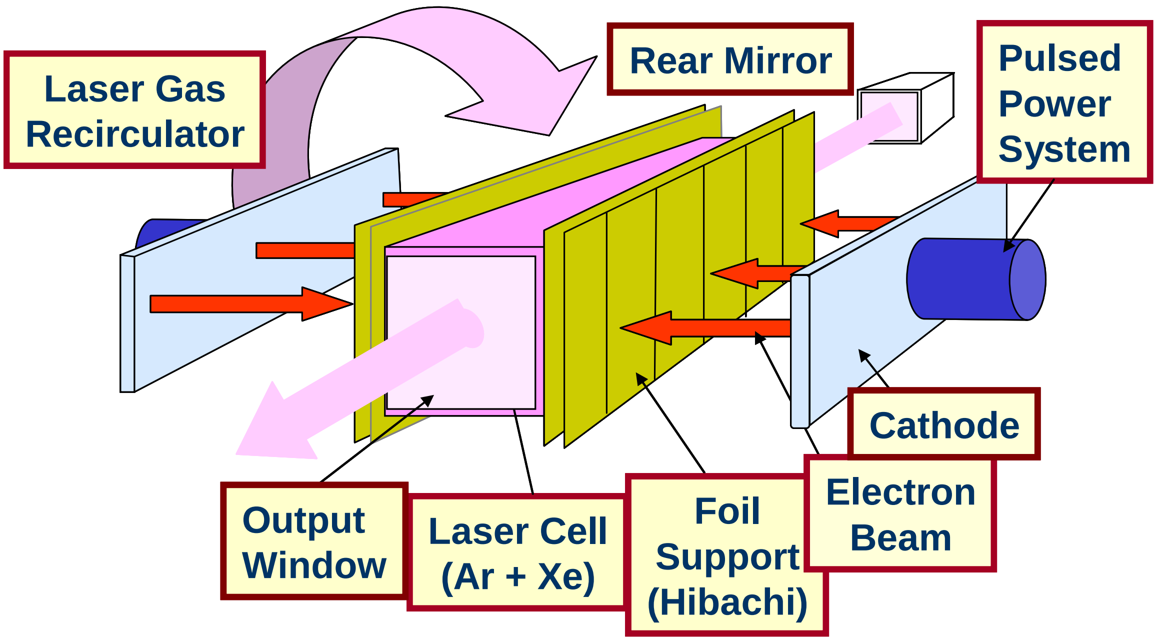

FIG. 2. Diagram of Ar-Xe laser components as realized on NRL's Electra facility.

Though it is not optimized for Ar-Xe, Electra was an excellent platform to study the physics of this laser and identify the issues needed to scale Ar-Xe to DEW-class power levels. Furthermore, many of the technologies developed by Electra for DOE's laser fusion program are applicable to an Ar-Xe DEW HEL. The main relevant technologies are: rep-rated pulsed power, development of a gas recirculator, durable cathodes, and an efficient, cooled hibachi which can last for tens of thousands of individual pulses. In addition, an advanced, all solid-state 250 kV pulsed power demonstration system with efficiencies exceeding 80% has been developed which has operated continuously for

1,000,000 shots at rep rates up to 10 Hz. Thus, the Navy stands to benefit greatly from the 30-to-1 cost leverage described above.

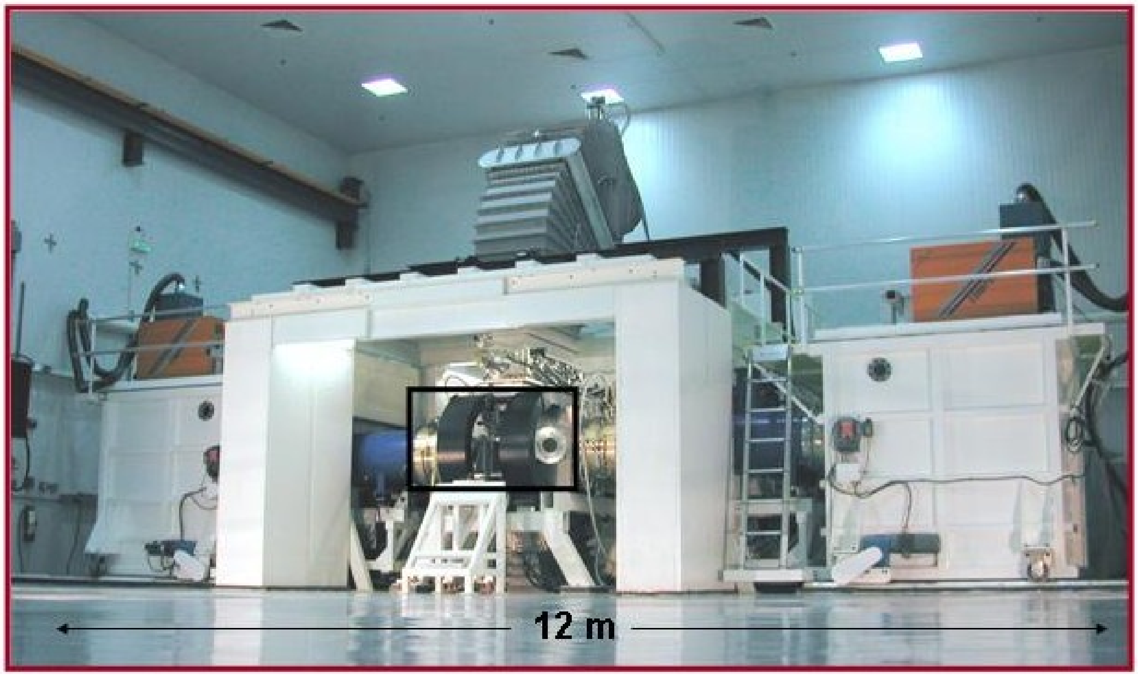

FIG. 3. Photograph of NRL's Electra laser. Rectangular region outlined in black indicates the area diagrammed in more detail in Fig. 2.

III. Objectives and Accomplishments of the NRL Ar-Xe 6.1 Program

The essential goals of the NRL Ar-Xe laser 6.1 program were: (a) Demonstrate the Ar-Xe laser on NRL's Electra facility, (b) Determine (within Electra's capabilities) the optimal operating conditions, coupled with an understanding of the basic kinetics and reaction channels that affect gain and efficiency, and, (c) Based on our studies, produce a concept design of a high power Ar-Xe laser system. A typical Ar-Xe laser experiment on

Electra employed a diagnostics suite schematically shown in Fig. 4. There is a time-integrating calorimeter to measure the total laser energy output, time resolving photodiodes to examine the laser pulse shape and its spatial variation, a pressure transducer which is used to unfold the beam deposition into the laser cell, and an interferometer to follow the electron density.

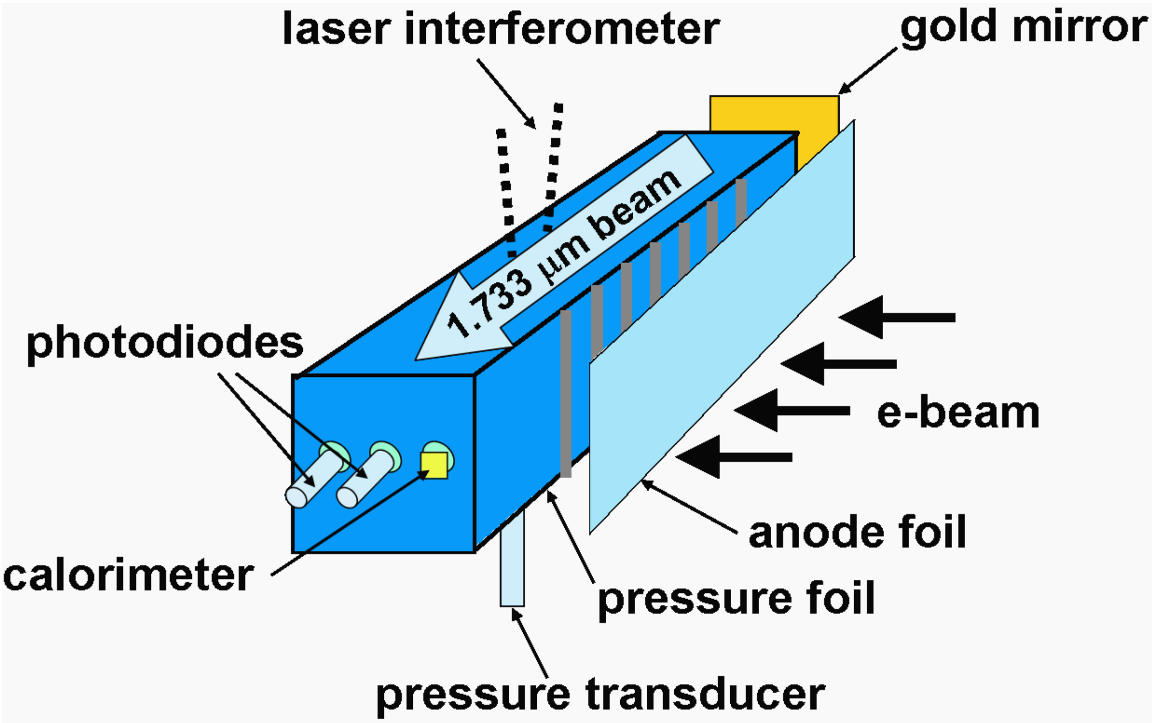

FIG. 4. Typical diagnostic setup for Ar-Xe experiments on NRL's Electra facility.

The comprehensive suite of diagnostics diagrammed in Fig. 4 resulted in the collection of a large quantity of data over 4 Electra Ar-Xe campaigns totaling 935 shots. Of course, not every instrument shown was deployed on every shot. An example of some of the most detailed data is shown in Fig. 5, where the experimentally measured intensity of the 1.733 μm laser light is depicted as a function of space and time. Such data was employed in conjunction with a model of the Ar-Xe laser kinetics to guide the choice of experiments and deduce the underlying physics that we need to know to optimize the laser.

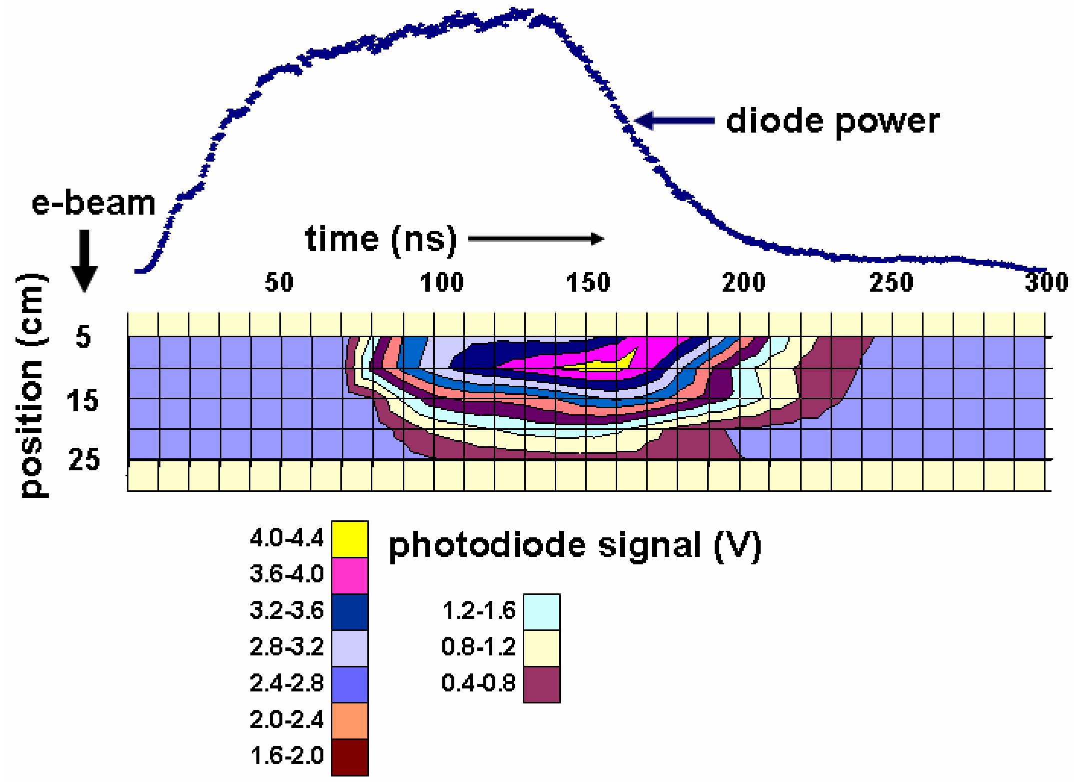

FIG. 5. Laser power at 1.733 μm is shown as a function of time and distance from the e-beam entrance foil (the pressure foil) for a one-sided pumping experiment. In this Electra shot, the total energy deposited was 577 J, the Xe fraction 1%, and the total pressure, 2.0 atm. The photodiodes were arrayed along the direction of e-beam propagation as shown in Fig. 4. The diode power is depicted in the curve shown above the power contours, on the same time scale.

We now summarize what we have learned. The scientific data and reasoning that justifies these conclusions has been presented in detail in Refs. 3-7, to which the interested reader is referred. Also, in its final year, the program's advances in the science of the Ar-Xe laser resulted in three invited talks [8-10] at national and international conferences.

- Repetitively pulsed lasing at 1.733 μm was demonstrated at 5 Hz, 45 W average power at 9 J per pulse. This was accomplished with only one side of the diode pumping the laser gas. With two sided pumping and further fine adjustment of the voltage and foils, we are confident that powers of at least 100 W could have been achieved, if resources and time had permitted.

- The electron beam power deposition density that maximizes the efficiency of the laser is 50-100 kW/cm^3. Note, this is an order of magnitude smaller than Electra's capability of 700 kW/cm^3. Since Electra's pulse width is fixed at 140 ns, the only way to obtain the optimum power deposition density was to reduce the diode voltage and use thick anode and pressure foils, in effect throwing away much of the available energy. This would not be necessary with an optimum pulsed power design which would spread the energy over a much longer pulse, and thereby achieve larger laser energy output.
- The ionization fraction during lasing was found by interferometry to be 10^{-5} to 10^{-4}. These data are the first measurements anywhere of the electron density during Ar-Xe lasing, and exceed by an order of magnitude the estimates of previous workers.
- This high ionization fraction, unexpected and unexplained by other laboratories' previous modeling of the Ar-Xe system, is in generally good agreement with our model, which employed modern atomic physics codes to calculate key rates. The single most significant limitation on our model is the uncertainty in key *molecular* rates which greatly influence the inversion kinetics. Some are not known even to within a factor of 2.
- Gain was measured and found to vary from 0.04 cm^{-1} at a Xe mixing ratio of 0.5% to 0.22 cm^{-1} at 2.5%.
- We settled a 20 year old debate by demonstrating that the ion Xe_2^+, in addition to $ArXe^+$, is responsible for creating the population inversion (Ref. 4). This demonstration also led to an understanding of the laser's behavior as a function of gas temperature.

- The intrinsic efficiency of the laser, defined as the emitted energy of the laser beam divided by the energy deposited by the electron beam, maximizes at a Xe mixing ratio of 1%. This efficiency increases rapidly with pressure and reached 3% at a pressure of 2.5 atm. *Electra cannot safely access pressures higher than 2.5 atm.* Fig. 6 shows the rapid improvement in laser performance with pressure. Each half atmosphere pressure increase has brought a 40% increase in laser yield.

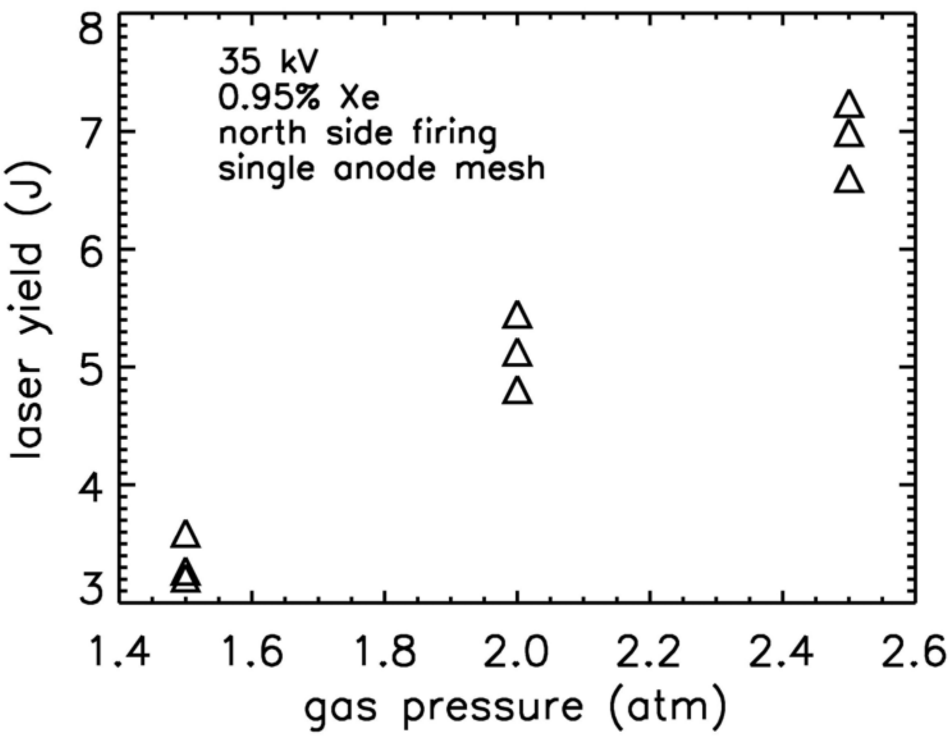

FIG. 6. Measured laser yield vs. gas pressure. As shown, we generally took 3 shots for each distinct set of experimental conditions on Electra. Subsequent use and adjustment of an anode foil increased the laser yield at 2.5 atm to 9 J.

IV. The Path to a Practical Shipboard DEW

The results of this 6.1 program to investigate the Ar-Xe laser suggest a path that could lead to a Naval Directed Energy Weapon. It consists of 5 principal steps, and is illustrated in a chart (Fig. 7) below.

R & D goal	Approach	Improvement factor relative to Electra's 45W	Facility/technical issues
Maximize the efficiency across entire cell	Optimize foils, hibachi, and voltage	2 - 3	Electra / electron transport, beam stopping in gas
Increase intrinsic laser efficiency	Test different kinetics (e.g., pressure, output coupler)	1.3 - 2	HAWK or similar/ test on laser cell with a pressure limit >2.5 atm
Longer pulse width	Extend to 2 μsec, instead of 140 nsec on Electra	15	HAWK or similar/ sustain optimal lasing conditions over the longer pulse
Higher rep rate	50 Hz instead of 5 Hz	10	Future: 25 kW system / foil and cathode durability, thermal management
DEW-class High Energy Laser ~ 1 MW	50 Hz, 2 μsec: Larger laser cell (1 x 1 x 3 meters)	33	Future: Full scale prototype / uniform e-beam deposition and extraction

FIG. 7. Suggested road ahead from the NRL Electra experiments, resulting in a 1 MW Ar-Xe laser, suitable for use as a shipboard DEW.

It is generally believed that power somewhere in the vicinity of 1 MW is needed for an effective laser DEW [11]. The third column of Fig. 7 gives a factor which is the power enhancement which would result from successful implementation of the corresponding phase of the overall program. Multiplying the factors together, and by the presently achieved 45 W, gives a power near 1 MW. The first phase, using two sided pumping and further improvement of the foils, with fine tuning of the optimum voltage, could have been done on Electra had time and resources permitted. It is the lowest risk of all of the steps presented, since pumping from both sides would have energized both halves of the laser cell, likely giving at least a factor of 2 power enhancement. The second phase would be aimed at taking advantage of the observed increase in efficiency and power with laser gas pressure, shown in Fig. 6. This phase cannot be implemented on Electra, since its safe

pressure limit is 2.5 atm. Recall also that the only way to obtain the optimum power deposition density of 50-100 kW/cm^3 on Electra was to discard some of its available energy, since its pulse width is fixed at 140 ns. In principle, the best use of the stored energy in a pulsed power generator to drive the Ar-Xe laser would be to modify the e-beam pulse width to optimize both the deposited energy and power. As mentioned above, this also cannot be done on Electra. However, there are existing long-pulse pulsed power systems which are well suited to optimizing the single-shot Ar-Xe laser performance. An example is the HAWK facility, which is also within NRL's Plasma Physics Division. HAWK is an integral part of the experimental facilities of the Pulsed Power Physics Branch, Code 6770. HAWK was built in 1990 at a cost of $500,000, and paid for by the Defense Nuclear Agency. It has been employed to investigate and develop high power x-ray sources, such as plasma Z pinches and bremsstrahlung diodes. It is pictured in Fig. 8. We envision the construction of a dedicated laser cell built to safely withstand pressures as high as 4 atm. The front end of HAWK could be mated to this new laser cell as shown in Fig. 9. Pulse widths at least as long as 800 ns, possibly longer, could be sustained on HAWK, thus enabling the testing of the Ar-Xe laser in promising regimes of higher power and longer e-beam pulse widths. There are also repetitively pulsed e-beam systems being developed elsewhere for microwave weapons (see, for instance, Ref. 12, p. 29). The final two phases of the overall concept for creating a 1 MW Ar-Xe laser would require investments in new dedicated systems. The fourth phase envisions a further increase in power of a factor of 10 brought about by increasing the e-beam pulse rep rate by that factor, from 5 to 50 pulses per second. Existing pulsed power gas switches can accommodate such a rep rate; the main questions surrounding this phase are of durability and thermal management. Two of the key engineering issues which arise in the design and implementation of such a system are the following. First, based upon the gas temper-

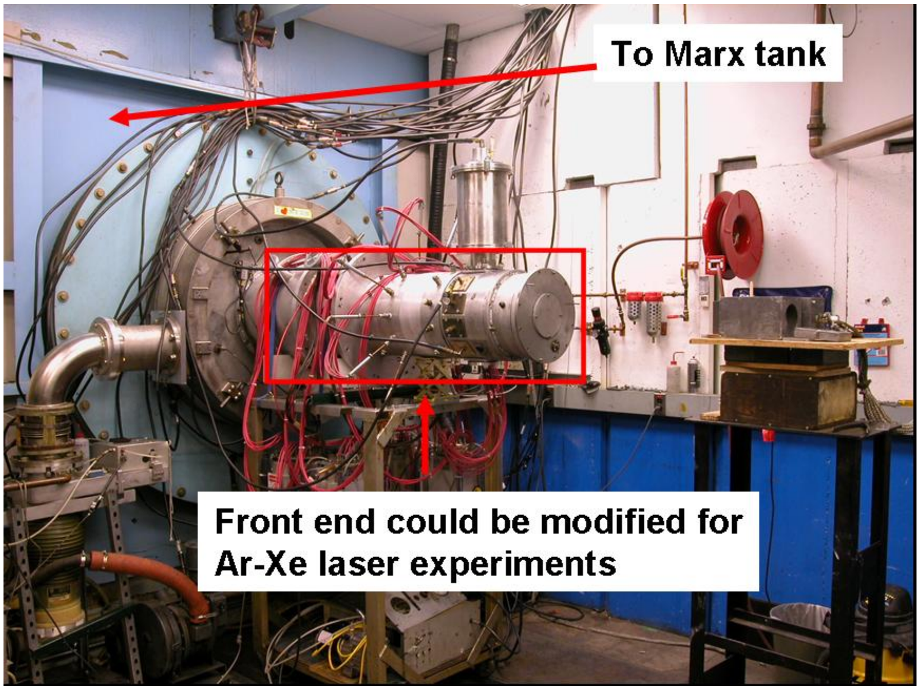

FIG. 8. The HAWK pulsed power generator, one of the experimental facilities of NRL's Pulsed Power Physics Branch, Code 6770.

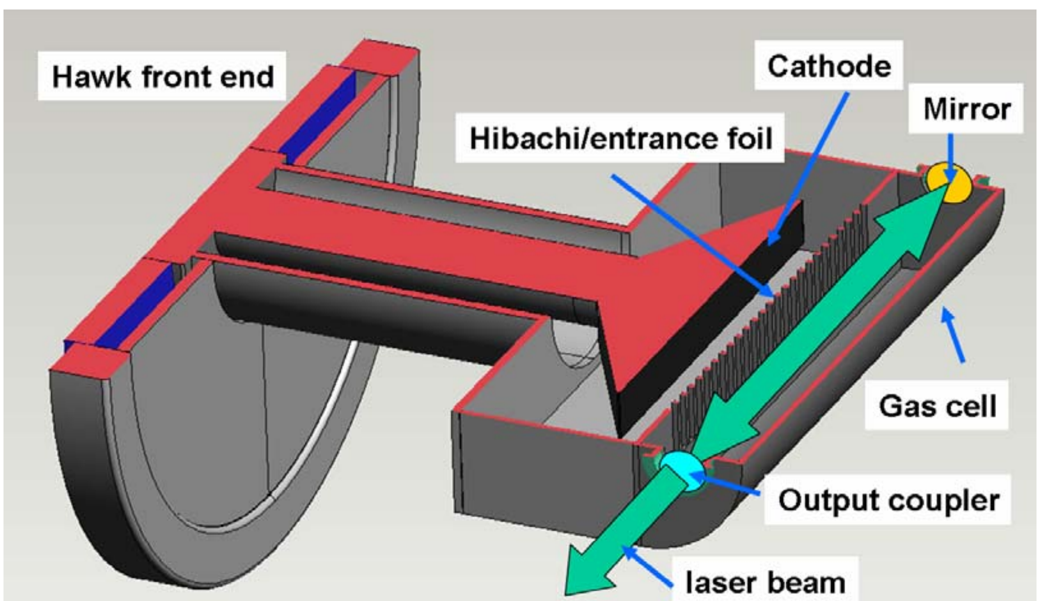

FIG. 9. A new, high-pressure laser gas cell could be mated to HAWK by flaring its inner conductor to form the cathode.

-ature dependence of the laser kinetics, we will need to recirculate the gas to keep it cool; this also would avoid any problems that might arise from turbulence. To completely replace the gas prior to each pulse at 50 Hz requires a flow velocity of about 30 cm/0.02 sec or 15 m/sec. Electra's recirculator typically operates with flow velocities of ~ 6-8 m/sec. The second key issue is thermal management of the hibachi foil. The system envisioned in the fourth phase will require about an order of magnitude more heat removal than has been demonstrated on Electra. This phase will either resolve these issues-paving the way to a practical shipboard Directed Energy Weapon- or lead to a program off-ramp. The fifth and final step to a 1 MW system is to build and energize a laser cell of dimension 1 x 1 x 3 m, which is 33 times the volume of Electra's. Fig. 7 is not intended to be a dogmatic or rigid technical path to an Ar-Xe laser DEW; many reasonable variants can be contemplated in developing the this laser to meet the critical Naval need of shipboard anti-missile defense.

V. Summary

Three decades ago, U. S. Navy tests demonstrated the promise of High Energy Lasers (HELs) in defending the Fleet against sea-skimming missiles. No HELs have yet been deployed because, until recently, no candidate laser appeared capable of simultaneously meeting the requirements for power, ruggedness to withstand a shipboard environment, atmospheric propagation, electrical drive, efficiency, beam quality, and safety. Present-day candidates which are under investigation include the free electron laser (FEL), incoherently combined fiber lasers, and the electron beam pumped Ar-Xe laser. In this report, we have presented the major results and discussed the implications of a 5 year 6.1 program at NRL to investigate the Ar-Xe laser.

The experiments were conducted on the Plasma Physics Division's Electra facility, which was designed as a rep-rated Krypton Fluoride laser for fusion applications. Though not ideally suited for the Ar-Xe laser, using Electra leveraged more than $50 M investment to date by the U. S. Department of Energy and also lead to significant advances in understanding the physics of this important and powerful infrared laser. Efficiency of 3% was demonstrated on Electra, whose laser gas pressure is limited to 2.5 atm. The efficiency increased at a rate of about 40% per half-atmosphere increase in pressure (Fig. 6). Other experimental facilities exist, some within NRL, in which the Ar-Xe laser could be tested at higher pressures and longer e-beam pulsewidths, which are the most promising avenues for further improvement in efficiency. The 6.1 program demonstrated that the Ar-Xe laser is a promising candidate, from both a practical and scientific standpoint, for shipboard anti-missile defense.

Acknowledgments

The authors gratefully acknowledge the contributions of and discussions with the following individuals: from NRL Code 6770, D Hinshelwood, R. Commisso, G. Cooperstein. From NRL Code 6720: G. Petrov, A. Dasgupta, J. Davis. From NRL Code 6730: M. Myers and the Electra team. From NRL Code 6700, S. Ossakow and R. Hubbard. From Commonwealth Technology: F. Hegeler, and from Berkeley Research Associates: Ts. Petrova and M. C. Coulter. This work was supported by the Office of Naval Research.

REFERENCES

1. J. .D. Sethian, M. Myers, I. D. Smith, V. Carboni, J. Kishi, D. Morton, J. Pearce, B. Bowen, L. Schlitt, O. Barr, and W. Webster, IEEE Trans. Plasma Sci. **28**, 1333 (2000).

2. P. Sprangle and J. Penano, MODTRAN 4 calculation.

3. K. Bartschat, A. Dasgupta, and D. H. Madison, Phys. Rev. A **69**, 062706 (2004).

4. J. P. Apruzese, J. L. Giuliani, M. F. Wolford, J. D. Sethian, G. M. Petrov, D. D. Hinshelwood, M. C. Myers, D. M. Ponce, F. Hegeler, and Ts. Petrova, Appl. Phys. Lett. **88**, 121120 (2006).

5. A. Dasgupta, J. P. Apruzese, O. Zatsarinny, K. Bartschat, and C. F. Fisher, Phys. Rev. A **74**, 012509 (2006).

6. G. M. Petrov, J. L. Giuliani, J. P. Apruzese, A. Dasgupta, Tz. Petrova, K. Bartschat, and D. Rose, J. Phys. D. **40**, 4532 (2007).

7. J. P. Apruzese, J. L. Giuliani, M. F. Wolford, J. D. Sethian, G. M. Petrov, D. D. Hinshelwood, M. C. Myers, A. Dasgupta, F. Hegeler, and Ts. Petrova, J. Appl. Phys. **104**, 013101 (2008).

8. "Recent Progress in Calculations of Electron-Impact Excitation of Rare Gases and its Impact on Gaseous Electronic Applications", presented by A. Dasgupta at the 60th annual Gaseous Electronics Conference, Arlington VA, October 2007.

9. "Electron Beam Pumped Lasers for Fusion Energy and Directed Energy Applications", presented by J. D. Sethian at the Tenth Annual Directed Energy Symposium, Huntsville AL, November 2007.

10. "Electron-Impact Excitation of Complex Atoms: Impact on Gaseous Electronics Applications", presented by A. Dasgupta at the 39th Annual Meeting of the American Physical Society Division of Atomic, Molecular, and Optical Physics, State College PA, May 2008.

11. J. R. Albertine, "Introduction to Directed Energy Issues: HEL Tutorial", presented at Directed Energy Professional Society Workshop, Crystal City VA, April 2003.

12. *High Power Microwave Sources and Technologies,* edited by R. J. Barker and E. Schamiloglu, (IEEE Press, New York, 2001).